

A Corporate Supersonic Transport

**Randall Greene
Aeronautical Systems Corporation**

&

**Richard Seebass
Aerospace Engineering Sciences
University of Colorado**

**Boulder Colorado
September 26, 1995**

**Transportation Beyond 2000:
Engineering for the Future**

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Introduction

Business aircraft manufacturers have been well rewarded in the market place for responding to technology, and thereby improvements in performance. Notable examples include the transitions to turboprop and turbojet aircraft as evidenced in the Gulfstream I and Learjet aircraft. The businesses that capitalized on these transitions were well rewarded.

No doubt over the past twenty years some have given considerable thought to a Corporate Supersonic Transport (CST). Gulfstream has, with the announcement of such an aircraft at Farnborough in 1988 and their 1991 announcement of a joint venture with Sukhoi to this end. Their market research indicated a substantial market for a 4000 nautical mile CST at \$60 million per aircraft.

This is a considerably different market than that for a commercial airline supersonic transport. In the second author's AIAA Durand Lecture,¹ he conjectured that for a supersonic transport to be economically successful, it would need to fly no more than Mach 1.5 - 1.6 and have the majority of its seats in business and first class. If it were to serve the growing international market for leisure travel, it would need to be an all wing aircraft flying obliquely, as suggested long ago by Lee² of Handley Page as a design for what became the Concorde. Careful studies by two design teams support these conjectures. A notable exception here are the very detailed studies by the Boeing Company.

The business market of interest here is smaller and better served by speed and airport flexibility. Overlooked in the Durand lecture was an aircraft he had considered long ago³ when seeking designs that might have a sonic boom that would be acceptable in overland flights, namely, a corporate supersonic transport. By 1970 the SR-71, with a nominal sonic boom overpressure of one pound per square foot, had been flying over selected areas of the western US for some time. Complaints about these unannounced flights were few.

This paper derives from a carefully considered study of the possibility of a corporate supersonic transport, conducted largely by the first author. It presents the non-proprietary aspects of a possible Corporate Supersonic Transport (CST). Such a CST could begin service as early as 2000. This project will require considerable technical assistance from NASA. Over a ten year production period this aircraft could accrue some \$15 billion in sales, with perhaps 40% of this amount being export sales.

Contents

The authors describe here, in brief, the strategies for developing a commercially successful CST, describe the potential market for such a business aircraft and the technology selected for its development. They then describe such an aircraft and delineate some missions for it.

The principal “show stopper” would seem to be the FAA certification of such an aircraft. The development of noise certification specifications for take off, and possible supersonic flight overland routes, are crucial to launching such an aircraft.

The authors conclude by suggesting some important roles for NASA in the development and eventual success of such an aircraft. We would note here that the roles NASA should play were well delineated by aircraft category nearly 15 years ago.¹ As civil supersonic aircraft go, the CST is “smaller, faster, cheaper.”

Strategy

Several strategies underpin this aircraft. One derives from the recognition that there are a considerable number of corporations as well as governments for which the opportunity to invest time elsewhere can bring a very considerable return in economic or political benefit. In addition, these opportunities are frequent and the number that can be capitalized on depends, to a considerable degree, on the speed of transportation available to these individuals. This is not speed at any cost, but speed with a high economic or political return.

A second strategy derives from the recognition that there is excess aircraft production capability among US defense contractors and that some of these have achieved extraordinarily efficient production.

Third, an “open skies” policy in this country makes business aircraft operations inexpensive and the development of a business aircraft less problematic here than elsewhere.

Fourth is the long US history of supersonic flight and an enormously rich technology base supporting it. That is not to say that the twenty years of commercial Concorde operations do not provide others with a very considerable base of experience. They do. Indeed, we are told the Concorde has more supersonic flight hours than all other aircraft, world-wide, combined. But this experience is less diverse, being limited to a relatively large transport based on the technology of the late 1950s.

While technological improvements continue, and a new aircraft should plan to eventually accommodate some, only well established technology should be used in an aircraft that pioneers certification in a new flight regime.

The Market

For FY 1993, the number of general aviation flights across the Atlantic alone was estimated to be 20,000.⁵ Forty percent of the NBAA member companies fly to Europe. A comparable percentage flies in the Pacific and to Asia. Over seventy percent fly to the Caribbean and Central America. Thus, there is a considerable market for a long range, high speed, business aircraft.

It seems to us very reasonable to assume a CST will garner at least 15% of the long range business fleet. This means more than 300 aircraft for corporate use alone. This, augmented by government travel, suggests a \$10 to \$15 billion dollar market if such an aircraft were available today. It is not. But the proposed CST easily could be available by the turn of the century.

Market - 2000-2010

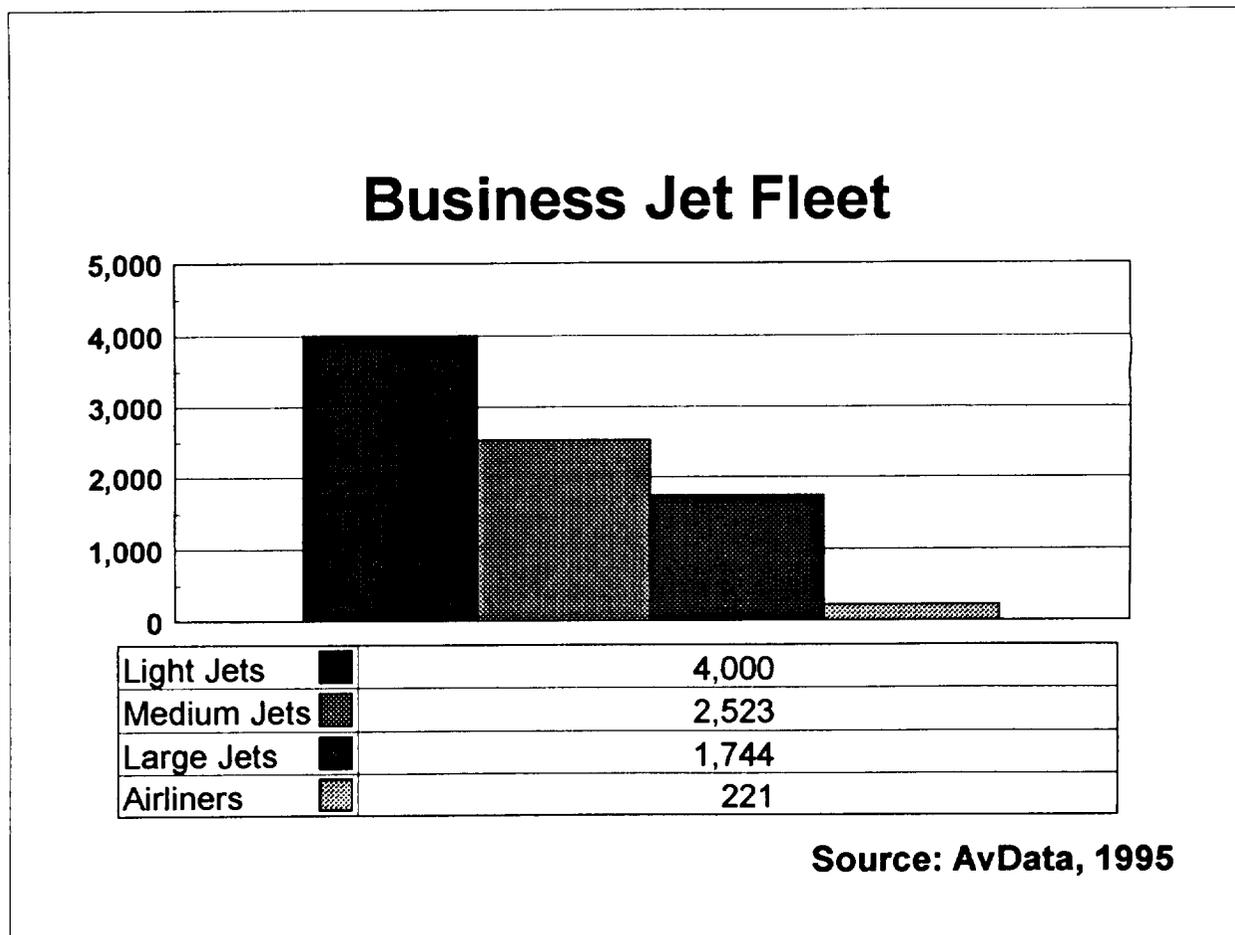
- Long Range & Mission-Enabled Applications
- 20,000 Atlantic Crossings/Year - Today
- 1/3 Projected Overland Useage
- Expand / Share Aircraft Long Range Fleet
- Corporate - 300+ Units
- Government / Special Mission - 50+ Units
- \$10-\$15 Billion Potential Market

US Business Jet Fleet

The US business jet fleet comprises some 8500 aircraft, and over half of these are of medium size or larger. The world-wide fleet is thought to be about 1400 aircraft, with a similar distribution in size.

For short flights, speed is not crucial. But it becomes important at longer ranges, which now require longer duration flights. Range is not the crucial ingredient here; time is. Some business jets will soon be capable of 6500 nautical miles. But at their speeds, this is a very long trip. An aircraft capable of the same distance, with a stop, in half the time has, we believe, considerable advantage.

Corporate fleet business travel continues to grow rapidly. The largest growth rate in business transport is for international travel. As world markets become increasingly international, an even larger fraction of business travel will occur in private aircraft.



The US Long Range Fleet

The US long range business fleet is some 2000 aircraft. World-wide this business fleet may be well over 3000 aircraft. Ninety percent of the National Business Aircraft Association (NBAA) owners use their aircraft for international flights. These trips would benefit greatly from increased speed. Any substantial increase in speed requires supersonic flight with the dual considerations of wave drag and sonic boom. The first of these compromises range; the second, if too large, would limit the available routes.

In this regard, two three-hour legs plus an hour long stop are much preferred by long range travelers than a twelve hour trip. We suggest that a CST will need to be two or more times faster than its subsonic competition for the value of time to offset the cost of this speed.

Long Range Fleet (> 3,000 nm)

- | | |
|-----------------------------|---------------------------|
| ▪ Corporate Aircraft | ▪ Airline Aircraft |
| – Gulfstream II/III/IV | – B707/727/737 |
| – Falcon 50/900 | – DC8/9 |
| – Canadair Challenger | – BAC 111 |
| – IAI 1125 Astra | – Others |
| – Hawker 1000 | ▪ 200 + Aircraft |
| – Others | |
| ▪ 1,800 + Aircraft | |

The Technology

The technology in the proposed aircraft includes well established aerodynamics, a known engine, and current materials.

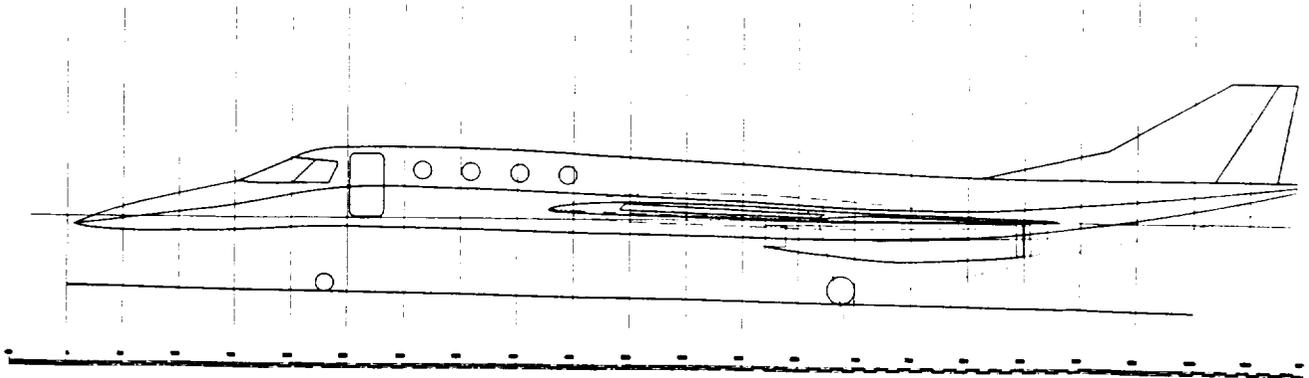
The cranked arrow wing planform is used most successfully on the F16XL. Natural flow wing design,⁶ an intuitive approach to area ruling, improves lift to drag. Aircraft shaping to minimize the equivalent perceived noise of the sonic boom frequently does this too. Minimum sonic boom perceived noise shapes are not minimum wave drag shapes, but they are often lower in wave drag than those now considered.

Technology

- **Aerodynamics**
 - Cranked Arrow Wing Planform
 - F16XL
 - Natural Flow Wing Design
 - Sonic Boom Shaping
- **Propulsion**
 - AlliedSignal F125-GA-100
 - ROC IDF
- **Materials - Current Technology**

The Aircraft

The first author's studies and knowledge of this market suggest that an eight to ten passenger aircraft with a nominal range of 3,350 nautical miles at Mach 1.8 would have considerable demand. Such an aircraft can capitalize as well on a higher speed for a shorter distance. The aircraft under current study is called the CST - 104A. It is the fifth iteration in our studies. Routes may be restricted by its sonic boom and, consequently, its range at near sonic Mach numbers is important.

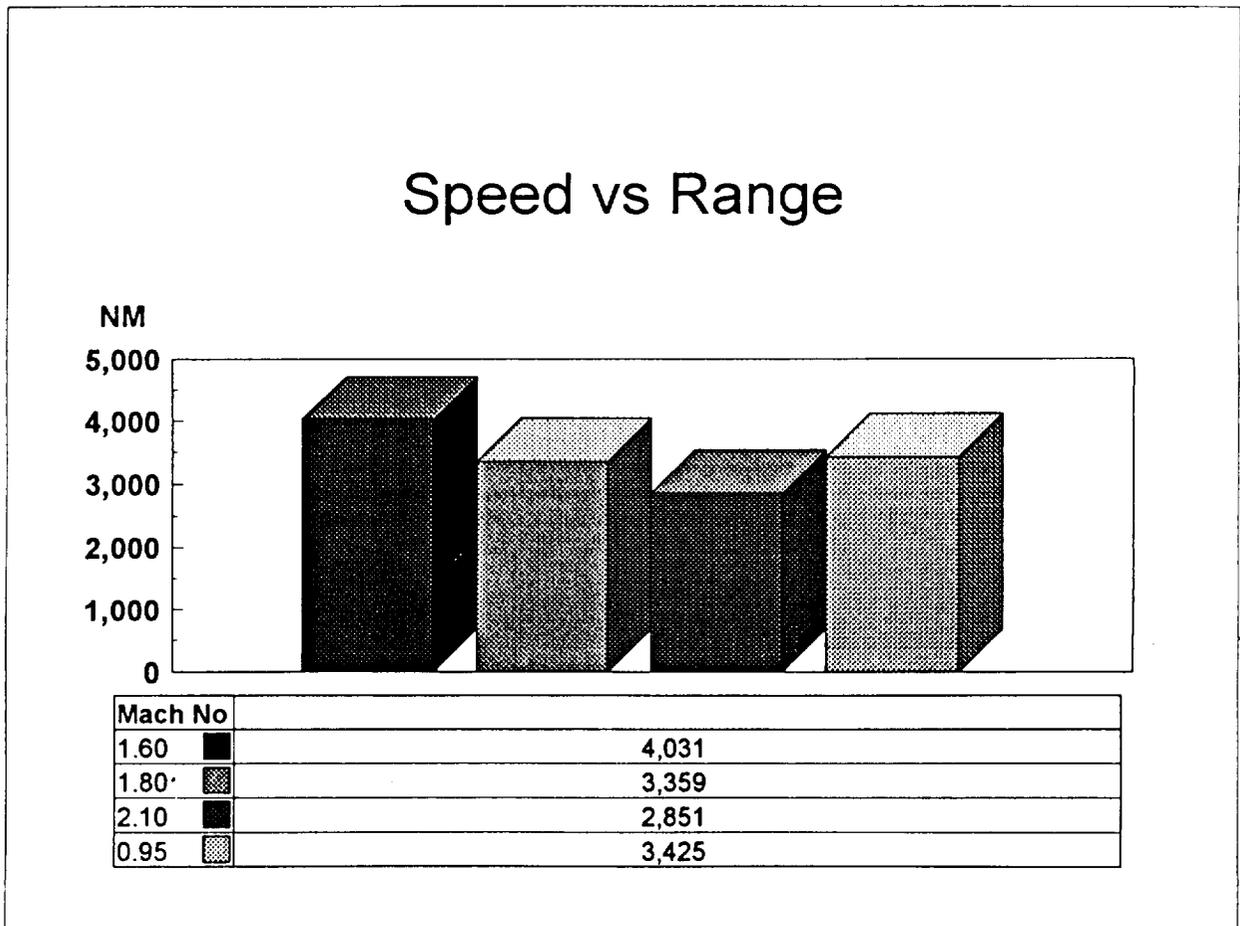


CST - Configuration 104A

- 8 - 10 Passengers (1,800 lbs)
- 3,350 nm Normal Cruise Range
- Mach 1.8 Normal Cruise Speed
- Speed / Range Flexibility

Speed and Range

Slower supersonic speeds provide longer ranges. At the 104A's maximum speed, corresponding to a Mach number of 2.1, its range is 2,850 nautical miles. At a Mach number of 1.6 it is just over 4,000 nautical miles. At $M = 0.95$, its range is 3,425 nautical miles, exceeding that at its $M = 1.8$ supersonic design point.



Size and Weight

The current configuration is 91 feet long and has a maximum takeoff gross weight of 66,000 pounds. This provides adequate space for eight to ten passengers plus crew. It would enter cruise above the tropopause with a weight of about 60,000 pounds. For this configuration the weights have been studied carefully.

Weights (lbs)

Structures	13,900
Propulsion	7,300
Systems & Equipment	5,100
Empty Weight	26,300
BOW	27,000
Payload	1,800
Max Zero Fuel Weight	28,800
Max Fuel	37,200
MLGW	37,200
MTOGW	66,000

Dimensions (ft)

Length	91
Height	18
Span	42
Fuselage Diameter (max)	6.5
Fuselage Fineness Ratio	14
Cabin Length	22
Cabin Width (max)	5.7
Cabin Height (max)	6.0
Cabin Volume (ft ³)	750

Sonic Boom

The connection between bodies of revolution with minimum wave drag for a given base area,⁷ volume and caliber,⁸ and three-dimensional aircraft was probably first recognized by Wallace Hayes in his 1946 CalTech Ph.D. thesis. But it only became clear with the 1955 NACA TN by Lomax.⁹ The aircraft shapes that minimize various sonic boom signature characteristics have been known for more than twenty years.³ The area distributions for minimum wave drag and those for various minimum sonic boom characteristics are not widely different. Thus a high L/D and low sonic boom are consistent with one another.

If the approximately 90 foot CST-104A begins its Mach 1.8 cruise at an altitude of 50,000 feet at a weight of 60,000 pounds, then, through careful design,³ its sonic boom overpressure could be as low as 0.4 pounds per square foot. It is lower at a lower Mach numbers, almost independent of cruise altitude (over the range 40,000 to 60,000 feet), increases nearly linearly with aircraft weight, and decreases nearly linearly with aircraft length.

Minimum Positive Phase Sonic Boom Overpressures

Overpressure lbs/ft ²	Weight lbs	Length ft	Altitude ft	Mach No
0.356	60,000	90	50,000	1.5
0.393	60,000	90	50,000	1.8
0.416	60,000	90	50,000	2.1
0.340	50,000	90	50,000	1.8
0.442	70,000	90	50,000	1.8
0.436	60,000	80	50,000	1.8
0.354	60,000	100	50,000	1.8
0.395	60,000	90	40,000	1.8
0.392	60,000	90	60,000	1.8

Seebass criterion; $W/L^{1.5} < 100, M < 1.6$, then overpressure can be less than 0.5 lbs/ft²

Mission

In a maximum range cruise mission at Mach 1.8, the aircraft needs only 24 minutes to cruise altitude and speed. It cruise-climbs for 2 hours and 45 minutes and then spends 32 minutes decelerating and landing, for a total flight time of 3 hours and 45 minutes to travel 3359 nautical miles. The average speed is about 90% of its cruise speed. Thus, for simple mission studies, we may approximate the time of travel using the cruise speed at the Mach number selected.

Mission Integration Summary - Mach 1.8 Cruise

Block	Altitude	KTAS	GW	Fuel	Range	Time
Start, Taxi, Takeoff	0	250	66,090	673	0	:11
Climb To Trop	36,089	556	65,417	2,598	69	:10
Supersonic Climb	43,998	1,032	60,976	1,843	43	:03
Cruise	46,890	1,032	36,063	24,913	2,912	2:49
Deceleration	46,890	688	34,617	1,446	229	:16
Descend / Land	0	250	33,944	673	104	:16
Total		941		32,146	3,359	3:45
Divert	43,827	545	30,671	3,274	200	:39
Loiter	15,000	325	28,840	1,831	0	:30

City Pair Missions

We depict here 8 city pair missions and approximate the travel times. The choice of Mach number is dictated by the range required. These trips are then compared with the travel times for the leading subsonic contenders. Travel times are typically 1/2 to 2/5 those for the subsonic jets. Stops were assumed to be one hour.

CST vs Subsonic Jets

Depart	Arrive	CST	900EX	G-V	GXP
Chicago	Los Angeles	1:12	3:06	3:06	3:06
Boston	San Francisco	1:54	4:48	4:42	4:36
Paris	Montreal	2:48	7:06	6:06	6:00
Riyadh	Singapore	3:42	8:30	7:30	7:30
Moscow	Washington	4:30	9:48	9:48	8:42
Tokyo	New York	5:42	12:48	12:48	12:48
Seattle	New Delhi	6:48	15:30	13:30	13:36
Brunei	Washington	8:48	21:00	17:56	17:12

City Pairs - Range / Speed / Time

Depart	Arrive	Range	Stops	Mach	Time
Chicago	Los Angeles	1,485	0	2.10	1:12
Boston	San Francisco	2,310	0	2.10	1:54
Paris	Montreal	2,915	0	1.80	2:48
Riyadh	Singapore	3,615	0	1.70	3:42
Moscow	Washington	4,210	1	2.10	4:30
Tokyo	New York	5,650	1	2.10	5:42
Seattle	New Delhi	5,990	1	1.80	6:48
Brunei	Washington	8,175	2	2.10	8:48

Technology Opportunities

This aircraft would be a likely candidate for laminar flow control. Laminar flow control could improve its performance considerably and it seems unlikely to be adopted on its subsonic competitors. Thus the advantage would be long lasting. Incremental improvements would come from higher turbine inlet temperatures, improved inlets and diffusers, and better shaping (area ruling) for reduced wave and induced drag.

Technology Opportunities

- **Engines**
 - SFCs
 - Temperature Margins
 - Nozzle/Diffuser Improvements
- **Aerodynamic**
 - Laminar Flow Control
 - Mach L/D vs Overpressure

Certification

The CST could be the first supersonic business jet. And it could well be the first supersonic civil airplane since the Concorde. FAA airport noise and sonic boom criteria for supersonic aircraft are lacking. The CST differs from an HSCT in several ways. For example, its takeoff and landing profiles differ considerably from an HSCT. For the CST-104A, takeoff is accomplished without afterburner.

Will a relatively modest sonic boom overpressure allow overland flight? What about the location of the boom from the CST acceleration to cruise? While this local focused boom might be half the sonic boom of an HSCT, its placement in relation to populated areas will have to be considered. Our long time focus on large supersonic transports has left many questions regarding a CST to be answered.

Show Stopper - Certification

- Overland Supersonic Operations
 - What's Acceptable?
 - Performance Penalty for Sonic Boom Reduction
- Airport (FAR 36)
 - Takeoff 92 EPNdB
 - Sideline 94 EPNdB
 - Approach 98 EPNdB

NASA's Role and the Next Steps

NASA has the expertise to be of considerable help in identifying and clarifying the noise issues for supersonic civil aircraft over a very large range of sizes, from the CST to the HSCT. With some better clarity on these issues, NASA has the expertise to help solve the problems identified.

A CST built with current technology requires the transfer of this technology to the manufacturer, as well as considerable assistance with wind tunnel testing and flight research. This aircraft must have flight handling qualities similar to those of subsonic business jets if it is to succeed.

The bottom line: It is NASA's role to make the US first in supersonic business jets and, while second in supersonic airliners, to now make the US first in economically successful supersonic airliners. Both are a considerable challenge. A CST is around the corner; an HSCT is a long way off.

Conclusions

The 2000 -2010 market for a CST would seem to be at least \$10 to \$15 billion. A considerable portion, although not the majority, of this market is export sales. This market is responsive to speed because of the considerable benefits of this speed.

The aerodynamic, avionics, control, propulsion, and structural technology bases exist within NASA, and other government agencies, to build a successful CST. The 104A conceptual design of such an aircraft is well advanced, including three two-engine and two four-engine studies.

With NASA's and the FAA's help, especially through their clarification of noise issues, and through technology transfer and other appropriate assistance from the government, a technically and economically successful CST can be, and should be, built.

Conclusions

- **\$1+ Billion/Year**
 - **Export Market**
- **Market Will Respond to Speed**
- **Technology Exists**
- **Engine is Mature**
- **Conceptual Design Advanced**
 - **3 2-engine configurations**
 - **2 4-engine configurations**

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About the Authors

Randall Greene is the President of Aeronautical Systems Corporation. Among its programs is the conceptual design of a Corporate Supersonic Transport. He was Founder and President of Commander Aircraft. Prior to founding Commander, he was at Allied Signal Corporation. He managed advanced systems, SDIO programs, and was director of international ventures and NATO marketing. He is an Associate Fellow of the Society of Experimental Test Pilots, and a Fellow of the Explorers Club. He is a former member of the Board of Directors of the General Aviation Manufacturers Association.

Richard Seebass is a Professor of aerospace engineering at the University of Colorado, where he was the Dean of Engineering from 1981 until 1994. An aerodynamicist and engineering educator, he has received the AIAA Durand, the IAF Malina, the University of Colorado and its College of Engineering Centennial, medals. He served on the NASA Advisory Council, the Air Force Scientific Advisory Board, and the Aeronautics and Space Engineering Board, which he also chaired. He is a member of the NAE and a Fellow of the AIAA.

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